# CMS searches for long-lived particles and other non-conventional signatures

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SUSY 2024

# Today's menu

- Many results from CMS. These are recent + personal preference

- In this talk:
  - Short chargino tracks: the only entirely SUSY signature
  - Heavy Stable Charged Particles: SUSY + Z'
  - Emerging jets: pions from the dark sector
  - Displaced dimuons: dark sector, RPV SUSY; improvements in Run 3 data

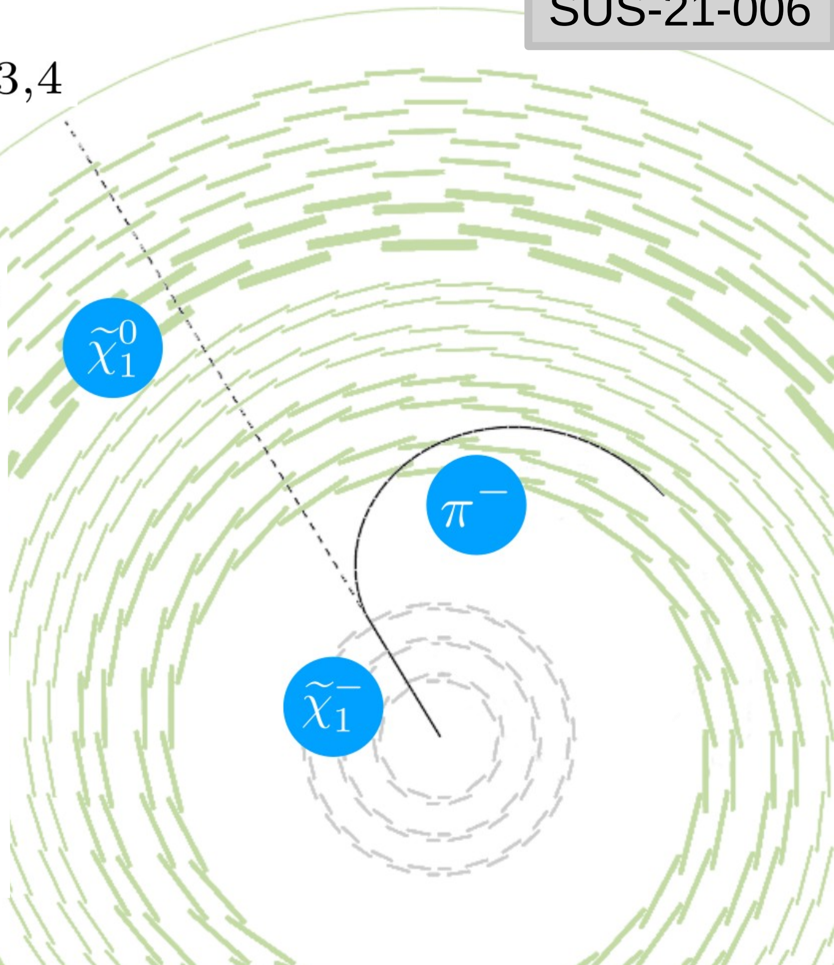
- Not mentioned:
  - Parking and scouting (ask me later :)

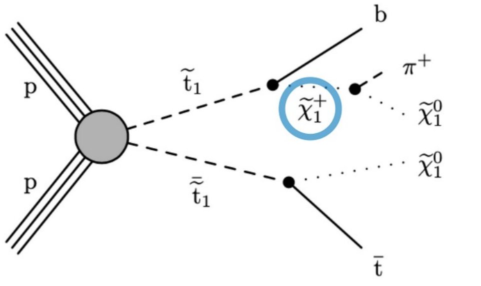
# Disappearing track: models + signature

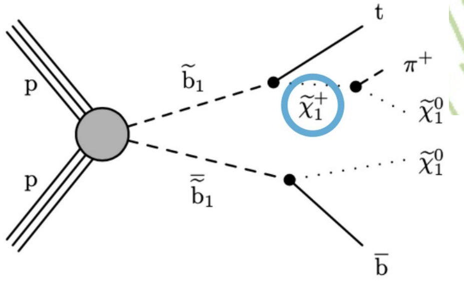
SUS-21-006

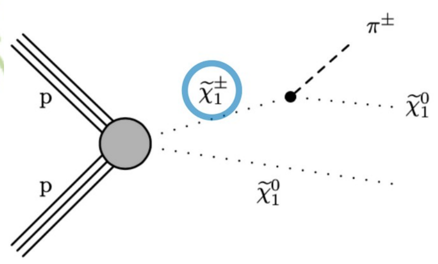
- Chargino mixing: $\tilde{W}^{\pm}, \tilde{H}^{\pm} \rightarrow \tilde{\chi}^{\pm}_{1,2,3,4}$
- Little mixing = compressed spectra
  - e.g., for pure Higgsino/pure wino LSP models
    - $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim$ 300 MeV
    - $c\tau(\tilde{\chi}_1^{\pm})$ up to 10 cm
  - chargino produced at the pp vertex
  - typical decay:

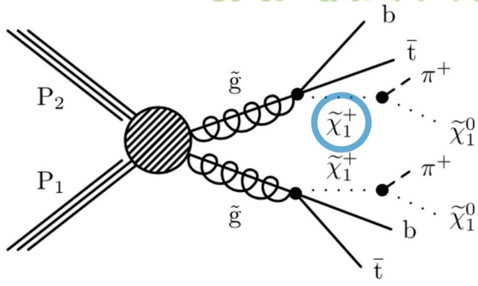

  - pion is very soft in lab frame, $\tilde{\chi}_1^{\pm}$ leaves track and “disappears”



# Disappearing track: Ionization observable

EXO-18-002

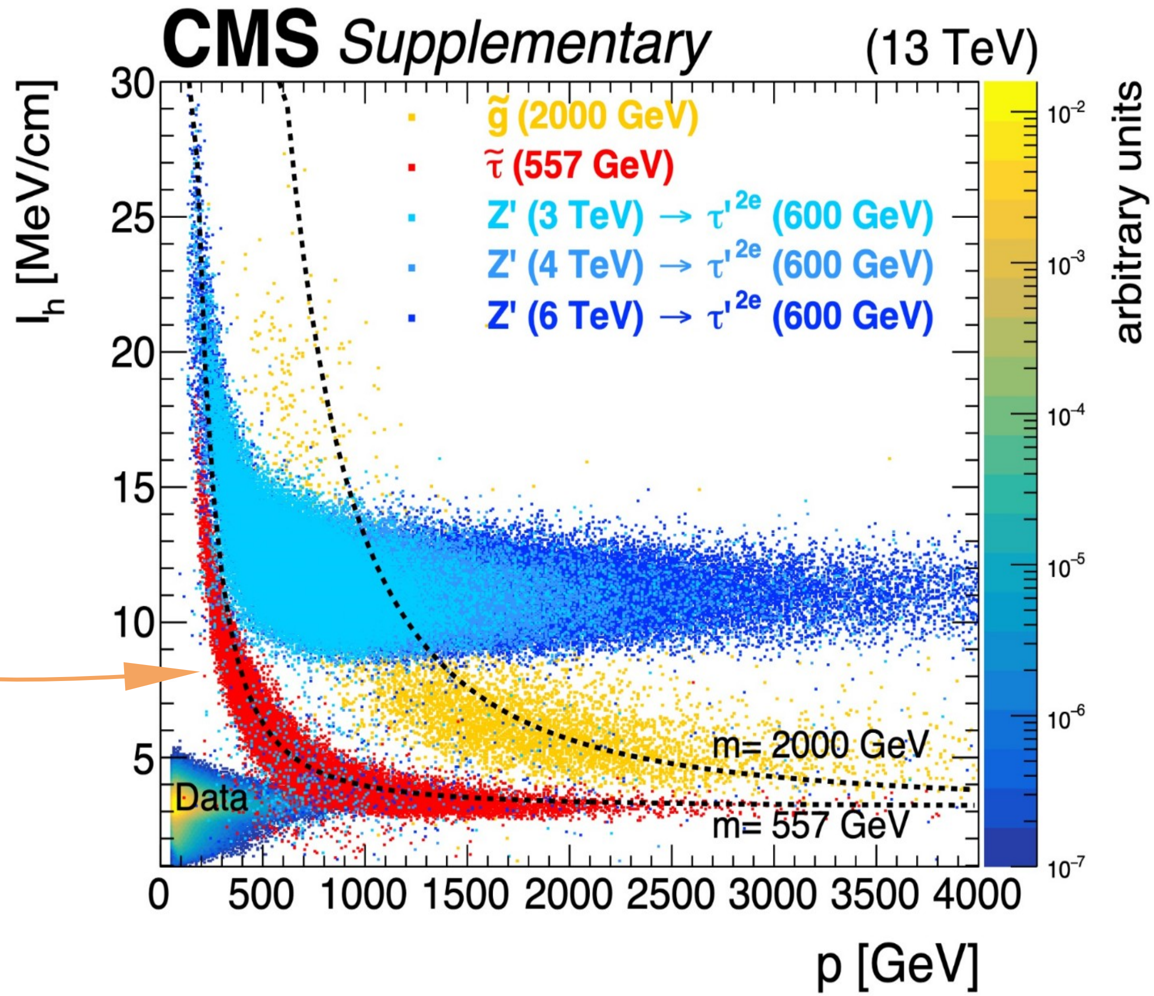
- Harmonic mean of $dE/dx$ (suppresses Landau tails)

$$I_\mathrm{h} = \left( \frac{1}{N} \sum_j^N (\mathrm{d}E/\mathrm{d}x_j)^{-2} \right)^{-1/2}$$

- Pixel + strip hits
- Approximation of Bethe-Bloch:

$$I_\mathrm{h} = K \frac{m^2}{p^2} + C,$$

- $K, C$ from a low- $p_T$ sample of $\pi, K, p$
- Also used in the HSCP search (next)

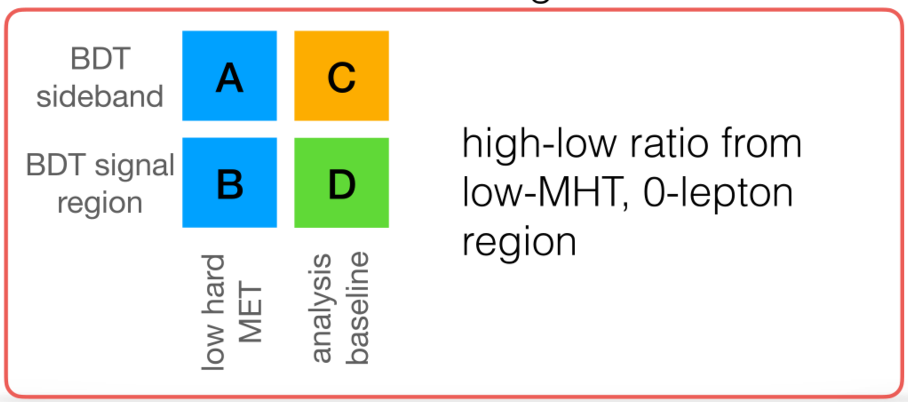


# Disappearing track: Event reconstruction

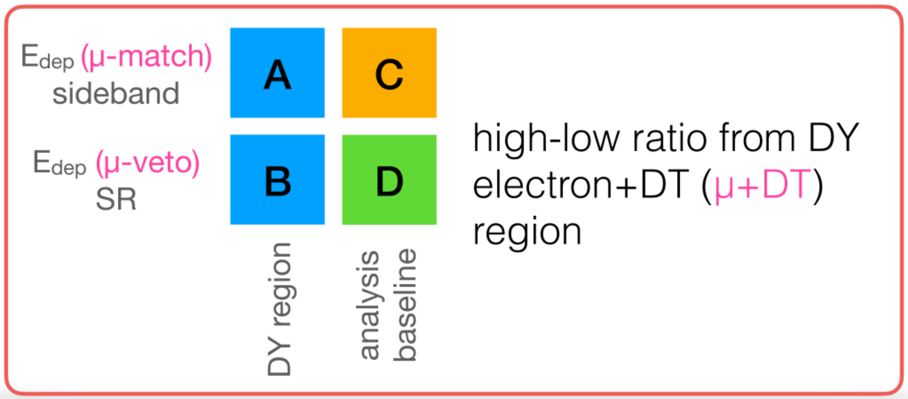
SUS-21-006

- Triggers: hard, isolated e or mu; or hard MET
- Separate BDTs for short (pixels only) vs long tracks (pixels + strips)
- Background estimation:

Fake track background



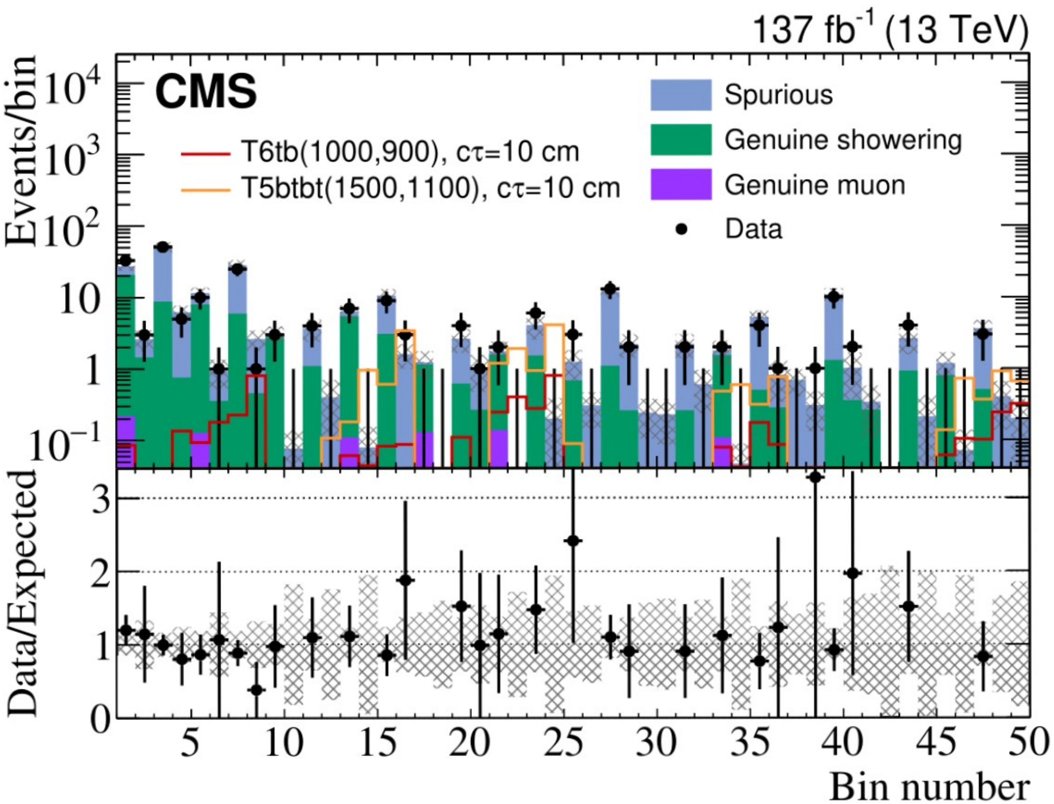

Prompt track background



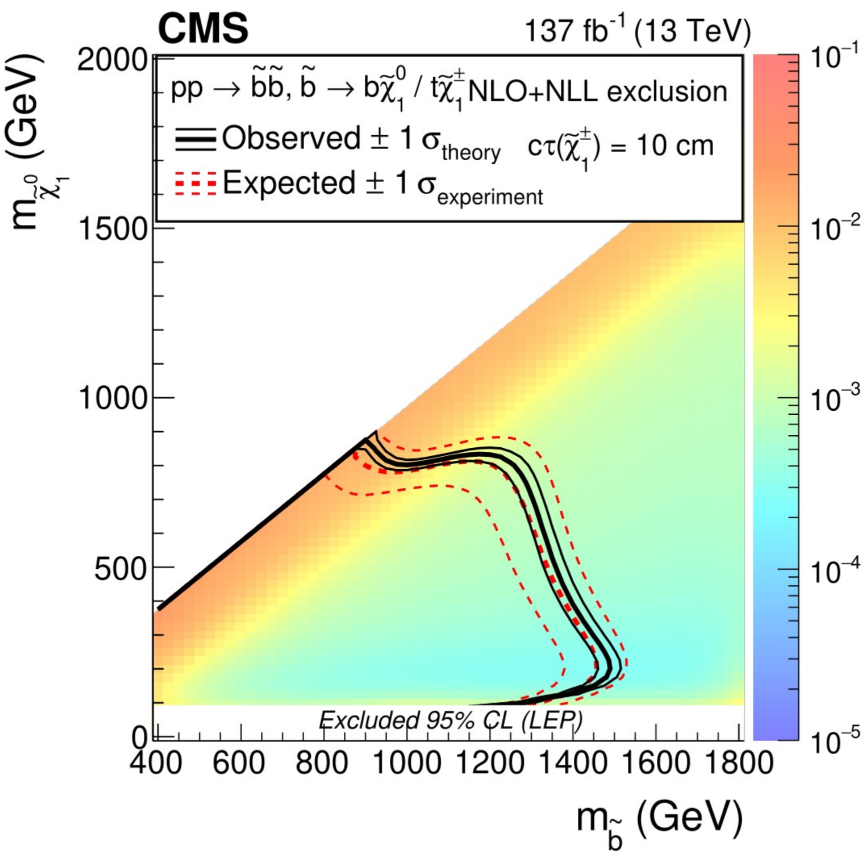

Signal regions binned in: hard MET | #jet, #btags | dE/dx low/high

# Disappearing track: Results

SUS-21-006




- Bkg dominated by spurious tracks
- In agreement with prediction :(

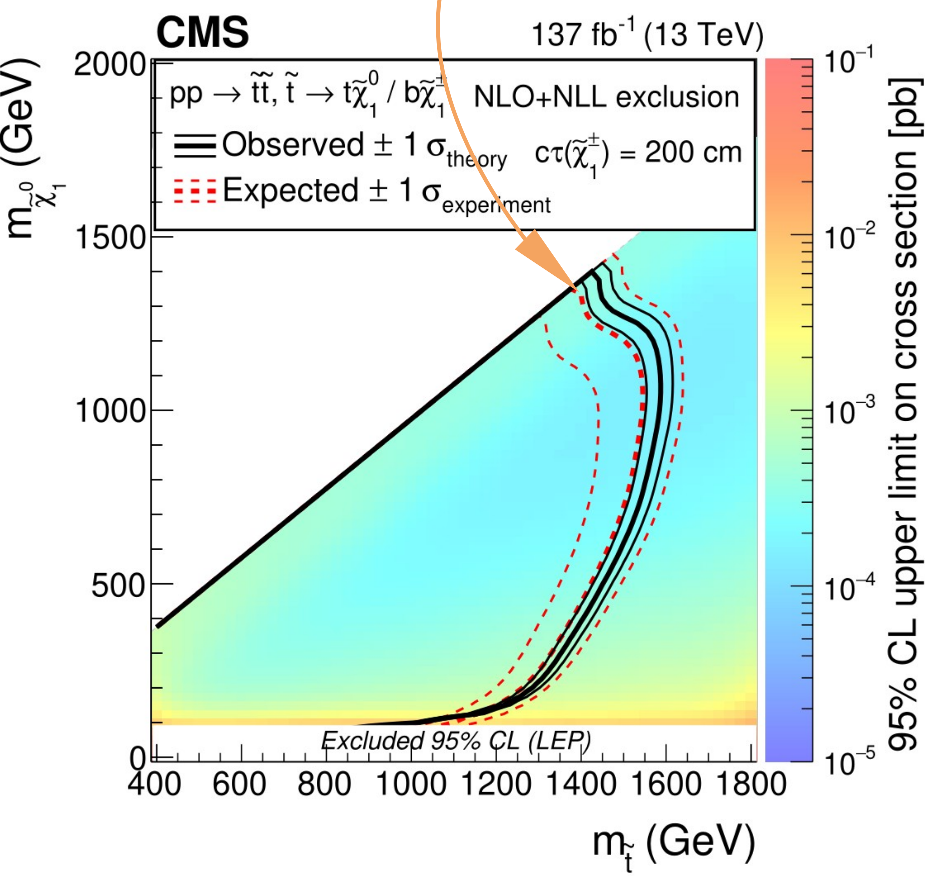


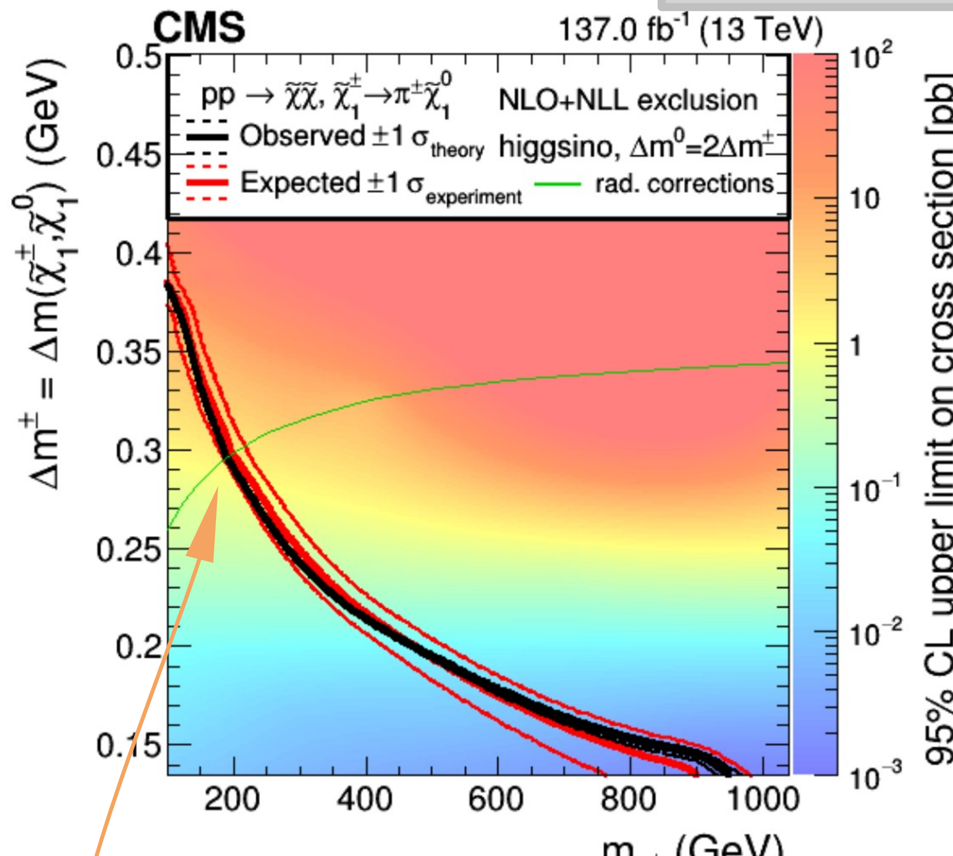

- Limits for gluino, stop, sbottom production
- Depend strongly on chargino lifetime. For: $c\tau = 10$ cm and $c\tau = 200$ cm

# Disappearing track: Results

SUS-21-006

Extended by hundreds of GeV compared with CMS hadronic search w/disappearing tracks



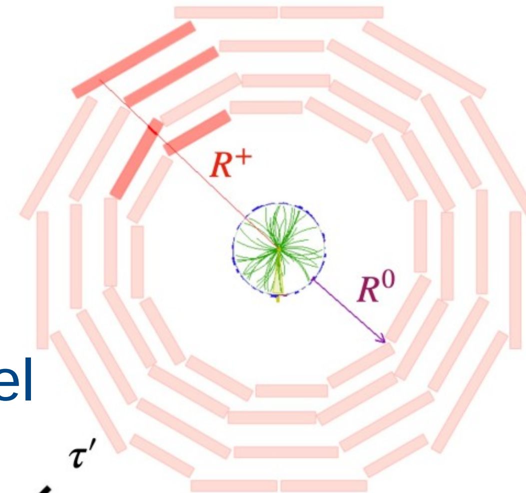



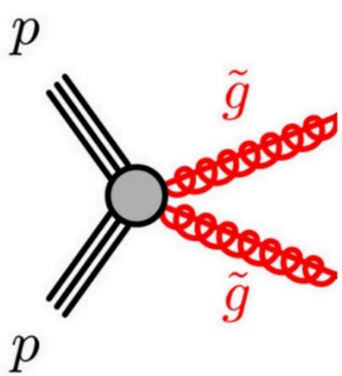

Pure wino DM model: excluded up to ~650 GeV
Pure higgsino DM: ~190 GeV

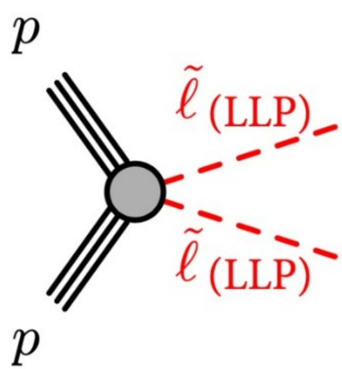
# HSCP: Models + signature

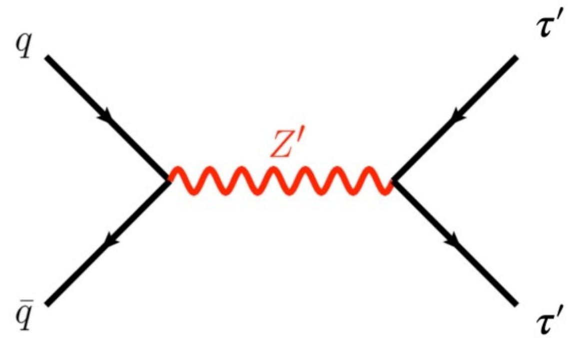
EXO-18-002

- Many models predict Heavy Stable Charged Particles (HSCP):
  - split-SUSY (R-hadrons with gluinos, stops)
  - GMSB/GGM SUSY (staus)
  - extra dimensions and fourth-generation BSM models ( $\tau'$ with Q=1e and 2e)
  - ATLAS excess motivated Z' to $\tau'$(2e) model




- Isolated track of high $p_T$ with large $\frac{dE}{dx}$ in the tracker

$\Rightarrow$ Signature-driven, model-independent search with many possible interpretations

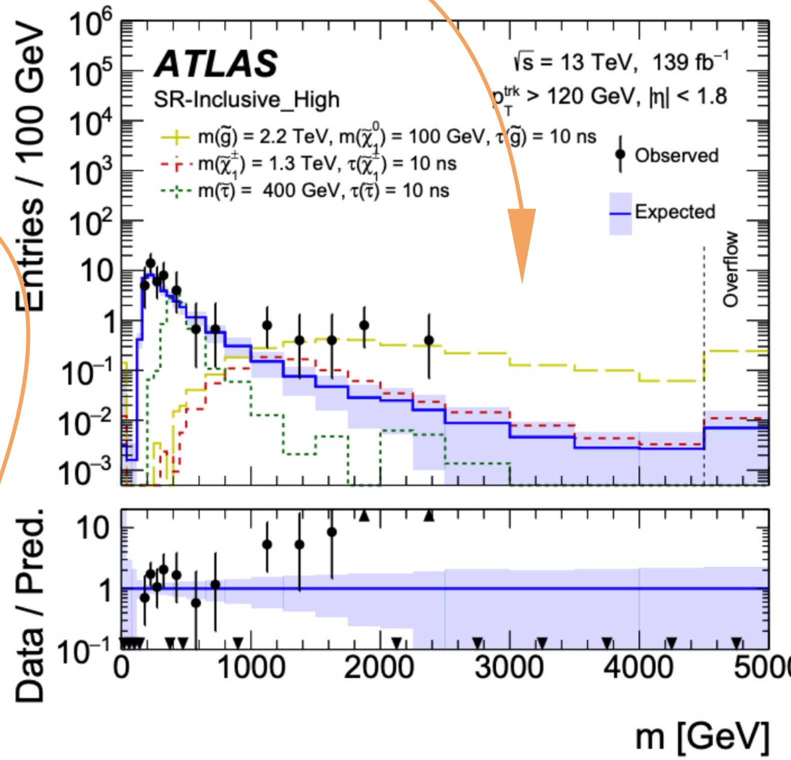
# HSCP: ATLAS excess

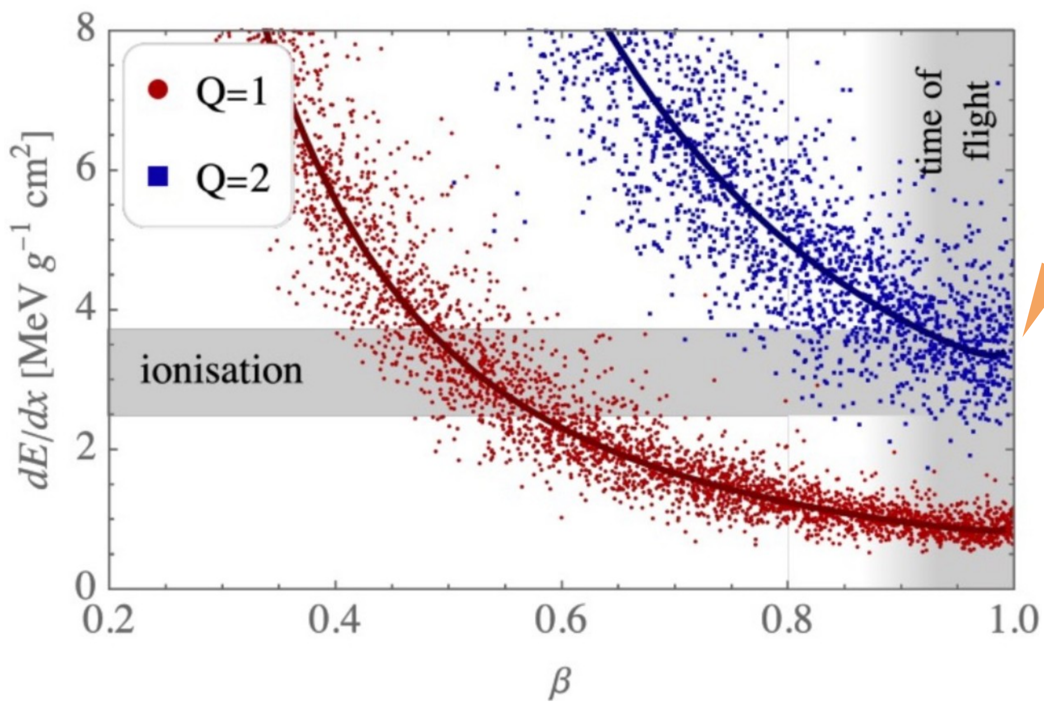
EXO-18-002

- $3\sigma$ excess (exp 0.7, obs 7), reconstructed as muons
  - However, $\beta \sim 1$, compatible with SM ("not slow")

2205.06013

- proposed explanation:
  Z' decaying into 4th gen leptons $(\tau')$ with Q=2e




2205.04473

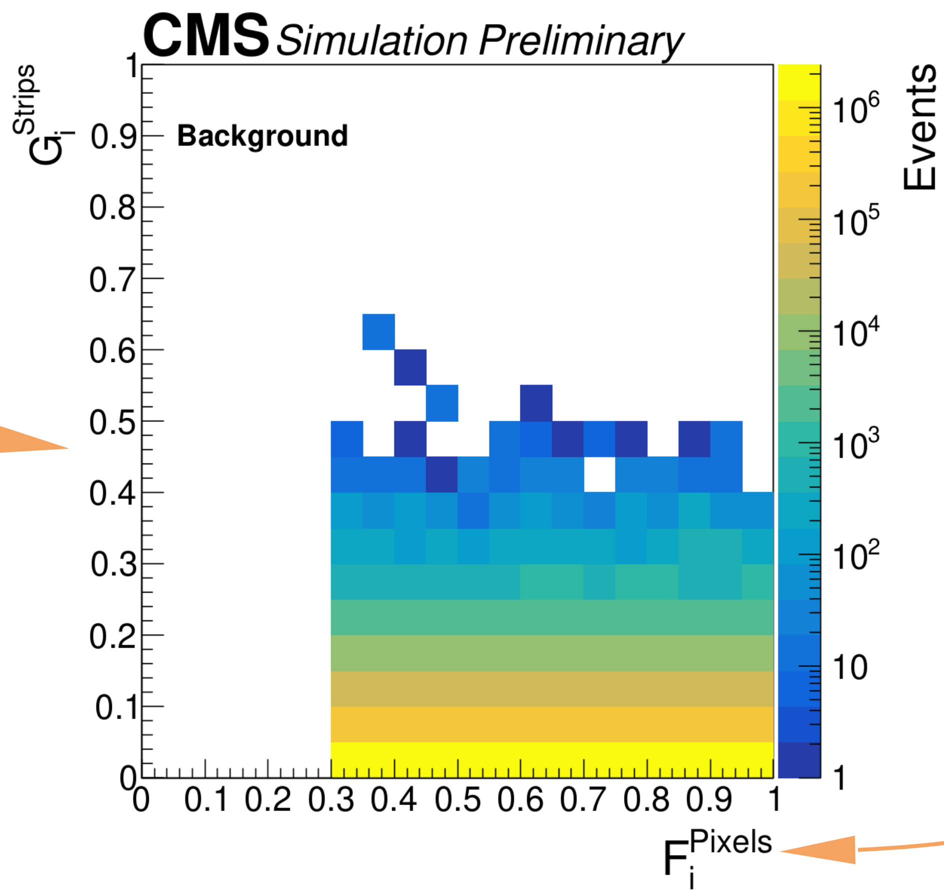
# HSCP: More ionization observables

EXO-18-002

- Pixels: $$F_i^{\text{Pixels}} = 1 - \prod_{j=1}^{n} P'_j \sum_{m=0}^{n-1} \frac{[-\ln(\prod_{j=1}^{n} P'_j)]^m}{m!}$$
- Strips: $$G_i^{\text{Strips}} = \frac{3}{N}\left(\frac{1}{12N} + \sum_{j=1}^{N}\left[P_j\left(P_j - \frac{2j-1}{2N}\right)^2\right]\right)$$

Flat for bkg!

Bkg steeply falling.



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EXO-18-002

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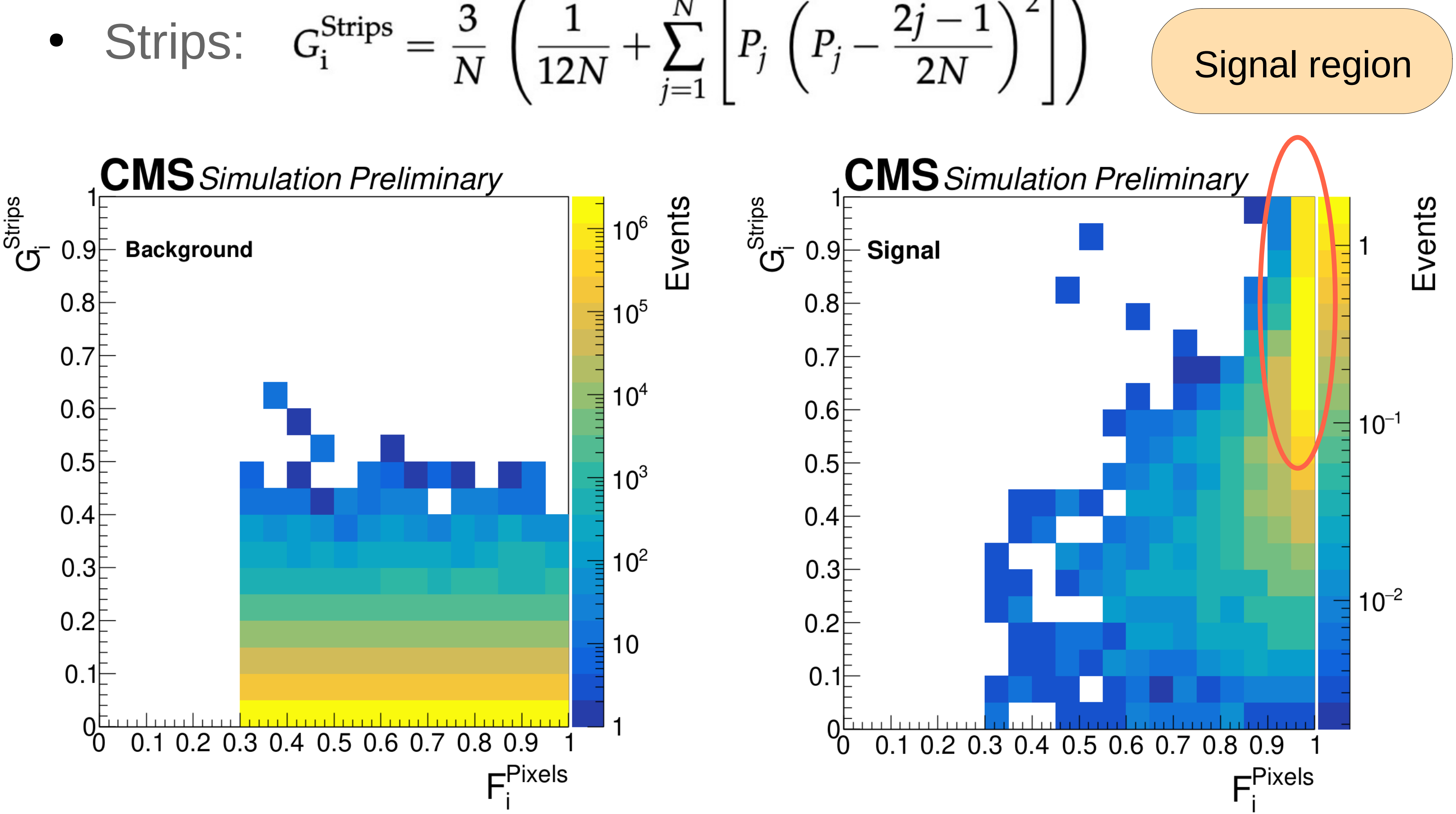


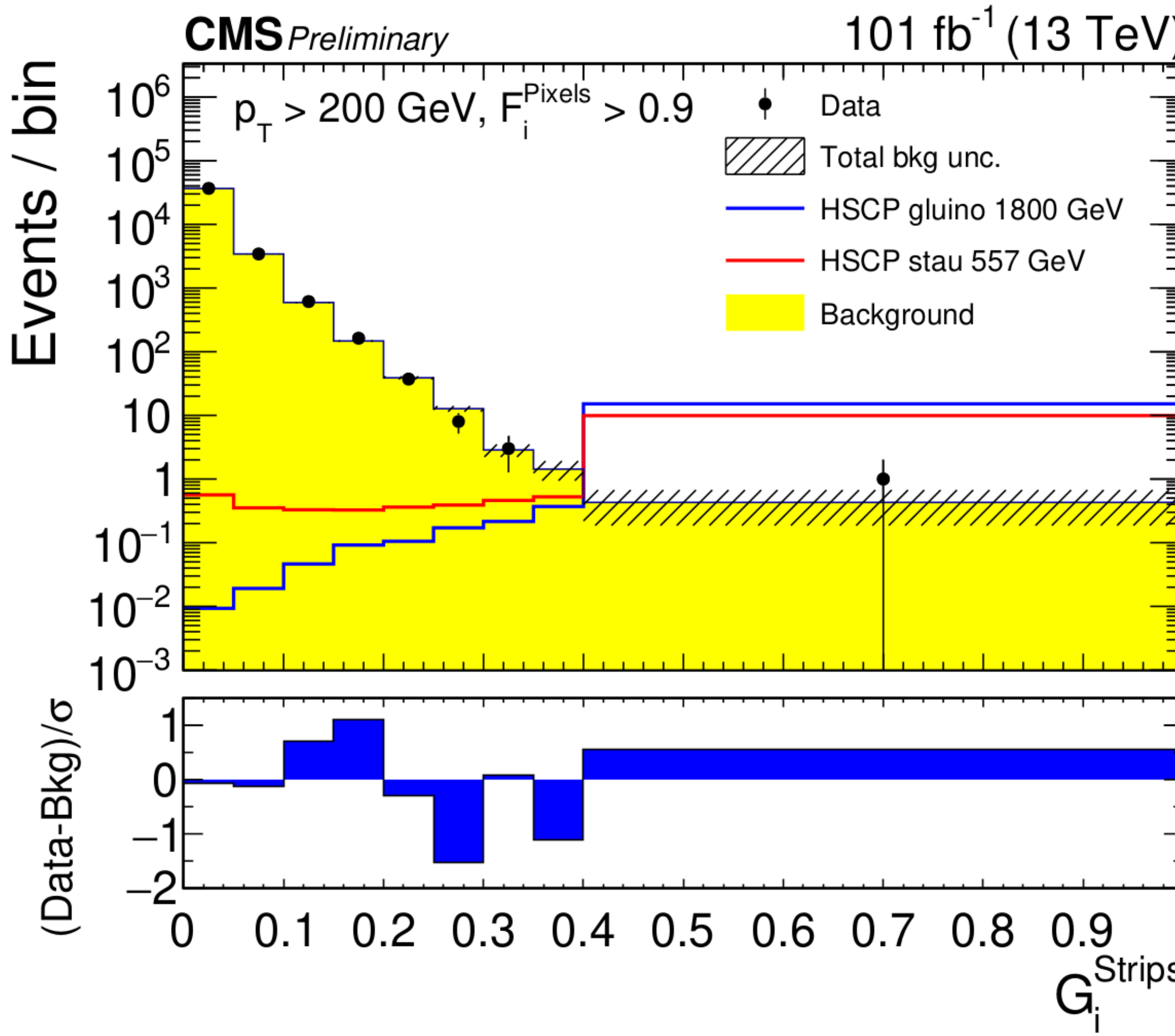
# HSCP: Bkg. Estimation #1

EXO-18-002

- $F_i^{Pixels}$ > 0.9; use the full shape of $G_i^{Strips}$ + $p_T > 200$ GeV

No significant excess above SM

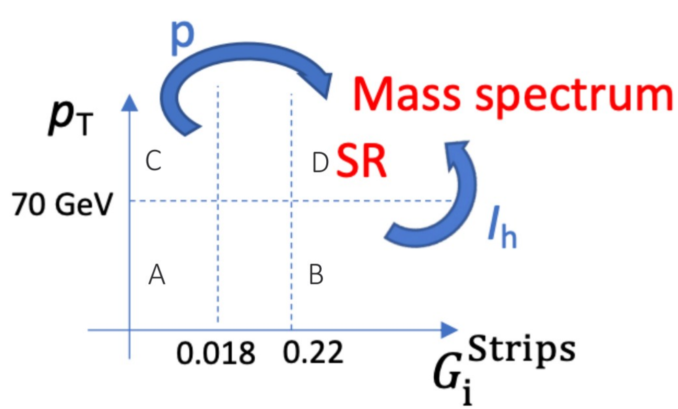
Last G bin: expected 0.4, observed 1



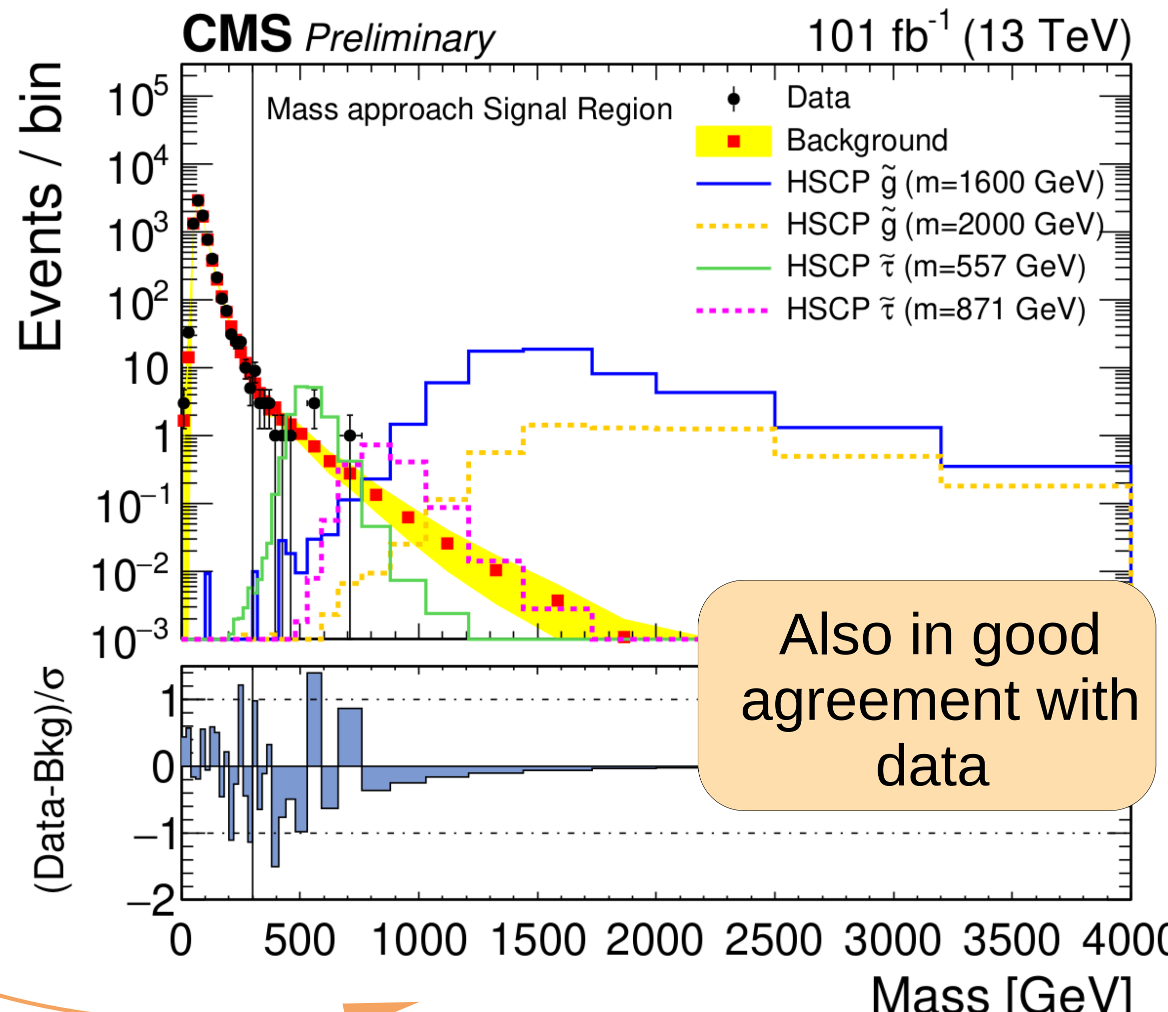
# HSCP: Bkg. Estimation #2

EXO-18-002

- Data-driven: assume independence of $I_h$ and $p$, and of $p_T$ and $G_i^{\mathrm{Strips}}$. Note lower $p_T > 70\ GeV$
  - ABCD method to determine every bin in mass spectrum



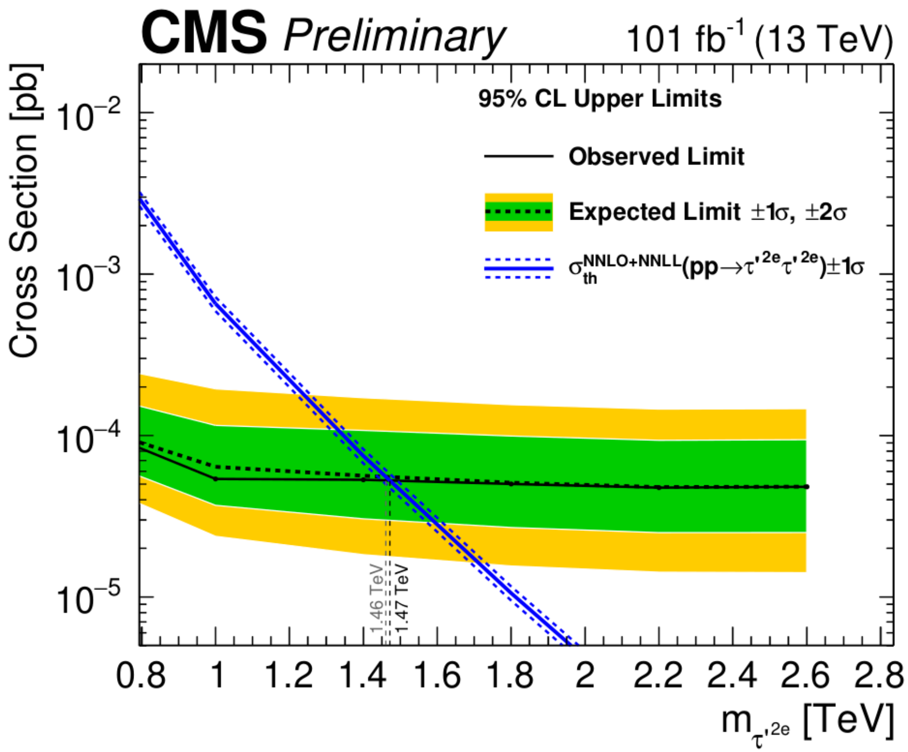

  - Counting experiment in dedicated mass windows



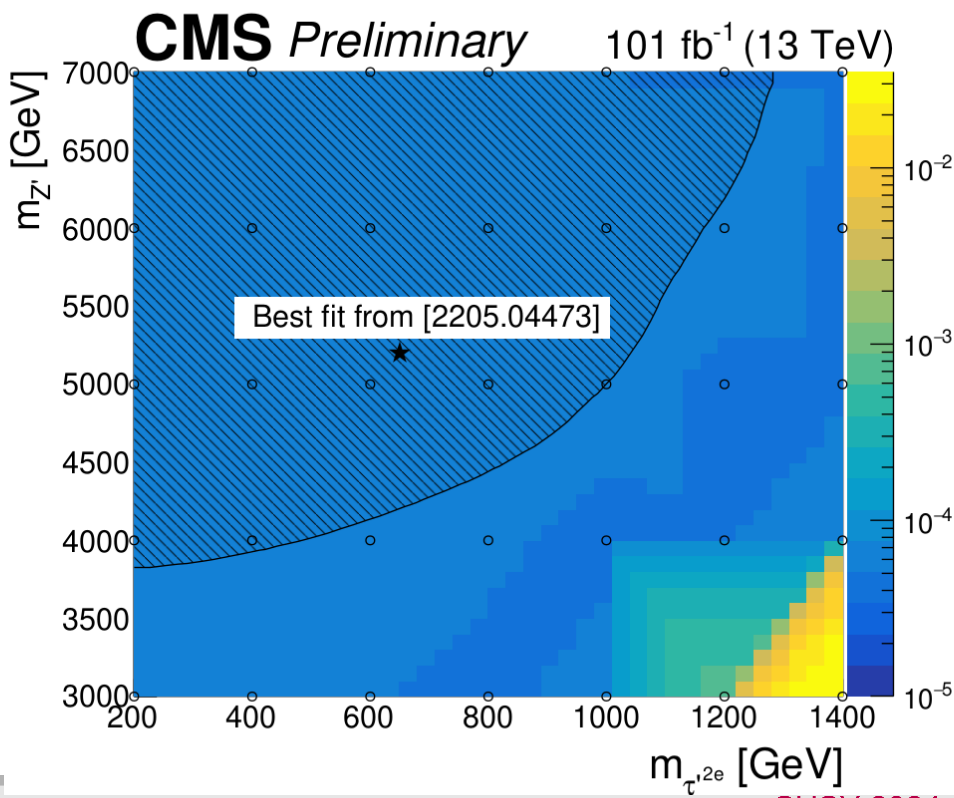

Also in good agreement with data

# HSCP: Results

EXO-18-002



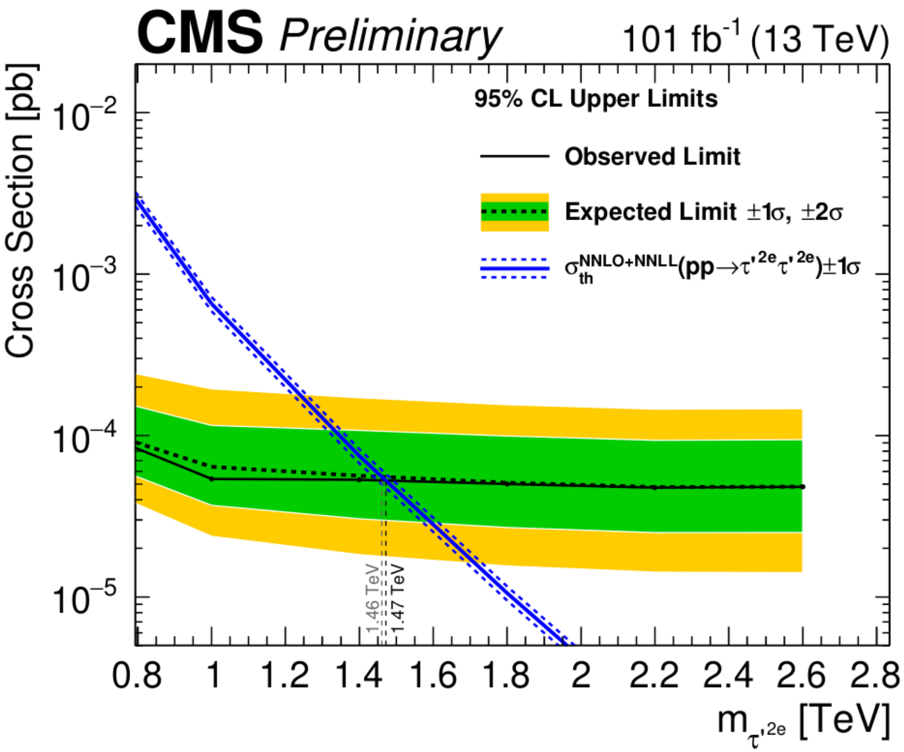

- Model (arXiv:2205.04473) created as an explanation of ATLAS excess: a highly ionizing track with $\beta \sim 1$
- (ionization method)




- DY produced $Z' \to \tau'\tau'$ (doubly-charged $\tau'$) mass > 1.47 TeV
- (mass method)

# HSCP: Results

EXO-18-002

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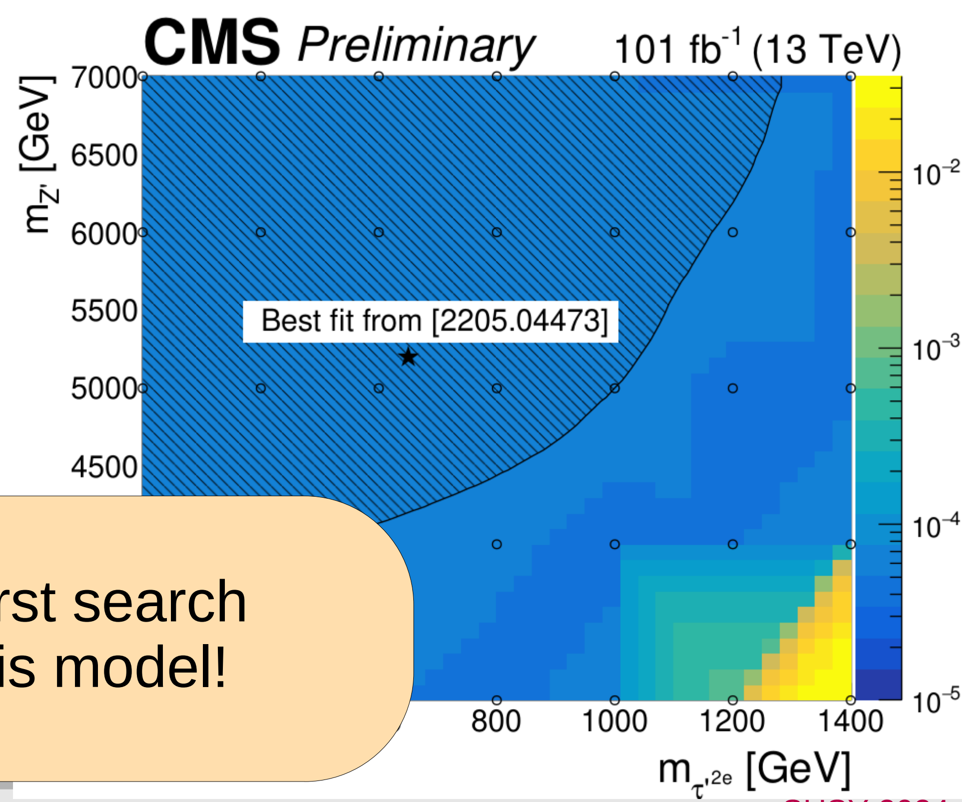


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- (mass method)

The first search of this model!

# HSCP: Results

EXO-18-002

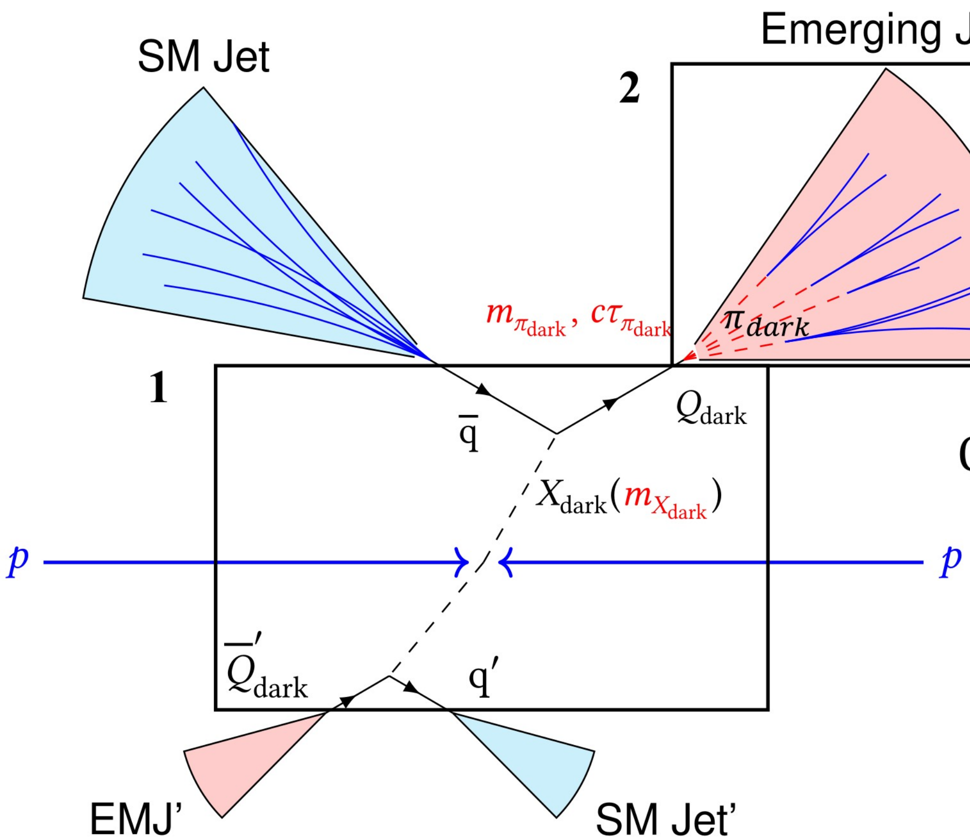
- X-sec limits: ionization method better limits at low signal masses
- While the mass methods is more efficient at large masses

| Model | Ionization method | | Mass method | |
|---|---|---|---|---|
| | Exp. (TeV) | Obs. (TeV) | Exp. (TeV) | Obs. (TeV) |
| $\tilde{g}$ | $2.08 \pm 0.09$ | 2.03 | $2.13 \pm 0.11$ | 2.13 |
| $\tilde{t}$ | $1.45 \pm 0.08$ | 1.40 | $1.51 \pm 0.10$ | 1.52 |
| GMSB $\tilde{\tau}$ | $0.88 \pm 0.07$ | 0.84 | $0.87 \pm 0.09$ | 0.85 |
| pair-prod. $\tilde{\tau}_R$ | $0.55 \pm 0.07$ | 0.52 | $0.52 \pm 0.07$ | 0.51 |
| pair-prod. $\tilde{\tau}_L$ | $0.68 \pm 0.08$ | 0.64 | $0.68 \pm 0.10$ | 0.61 |
| pair-prod. $\tilde{\tau}_{L/R}$ | $0.73 \pm 0.08$ | 0.69 | $0.75 \pm 0.10$ | 0.64 |
| $\tau'$ ($Q = 1e$) from DY prod. | $1.06 \pm 0.10$ | 1.02 | $1.18 \pm 0.12$ | 1.20 |
| $\tau'$ ($Q = 2e$) from DY prod. | $1.44 \pm 0.17$ | 1.37 | $1.46 \pm 0.13$ | 1.47 |
| $Z'_{\psi} \rightarrow \tau' \tau'$ | $4.01 \pm 0.27$ | 3.88 | $4.20 \pm 0.29$ | 4.22 |
| $Z'_{SSM} \rightarrow \tau' \tau'$ | $4.56 \pm 0.28$ | 4.41 | $4.75 \pm 0.28$ | 4.76 |

# Emerging Jets: model + signature

EXO-22-015

- Dark mediator $X_{\mathrm{dark}}$ couples to both dark and SM sectors
- Dark pions decay to SM. Parameters: $m_X, m_{\pi_{\mathrm{dark}}}, c\tau_{\pi_{\mathrm{dark}}}$




$$pp \to 2X_{\mathrm{dark}} \to 2(q\,Q_{\mathrm{dark}})$$

$$Q_{\mathrm{dark}} \xrightarrow{\text{hadronizes}} \mathrm{N}\,\pi_{\mathrm{dark}} \xrightarrow{\text{travel } c\tau} \text{SM particles}$$

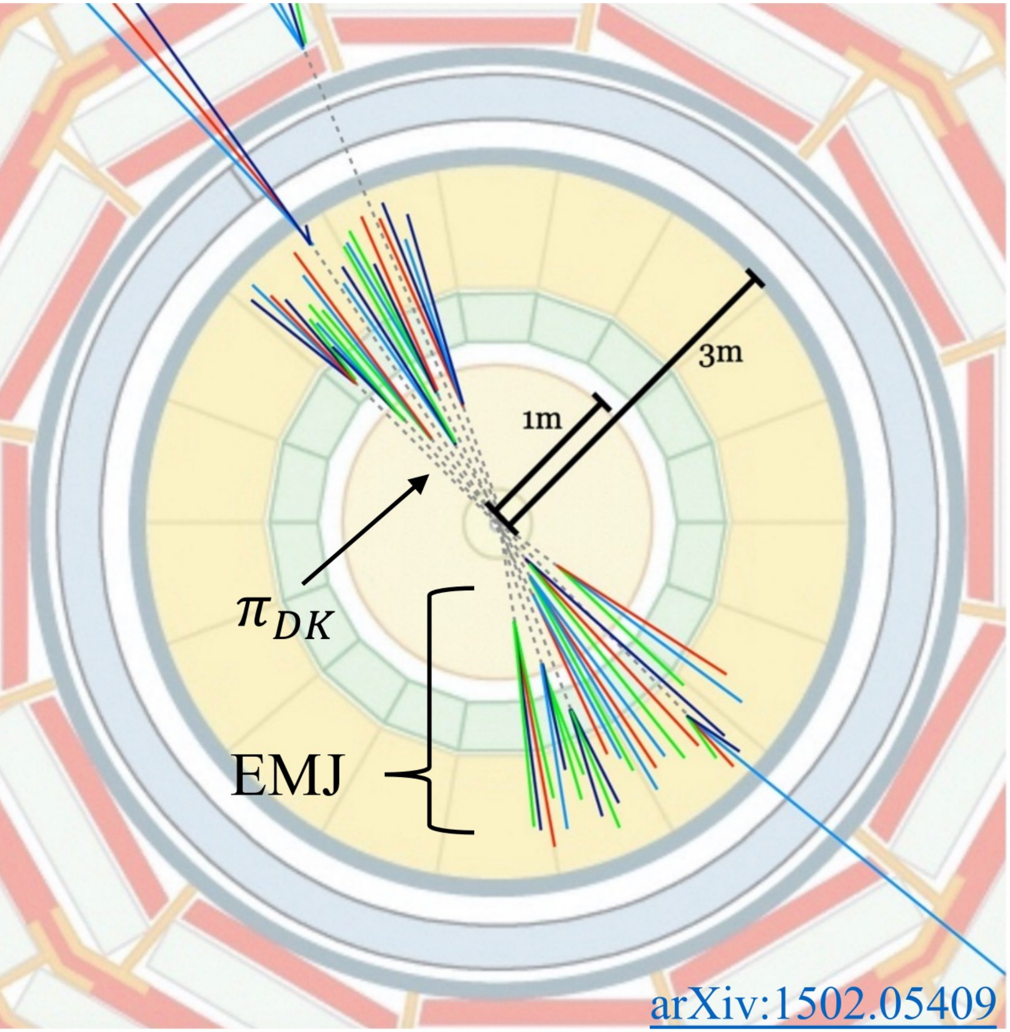
Two scenarios:

- Unflavored: $Q_{\mathrm{dark}}$ couples to d quark
- Flavor-aligned: $Q_{\mathrm{dark}}$ couples to d/s/b

# Emerging Jets: event reconstruction

EXO-22-015

- Large $H_T$; 4 high-$p_T$ jets, two tagged as EJ



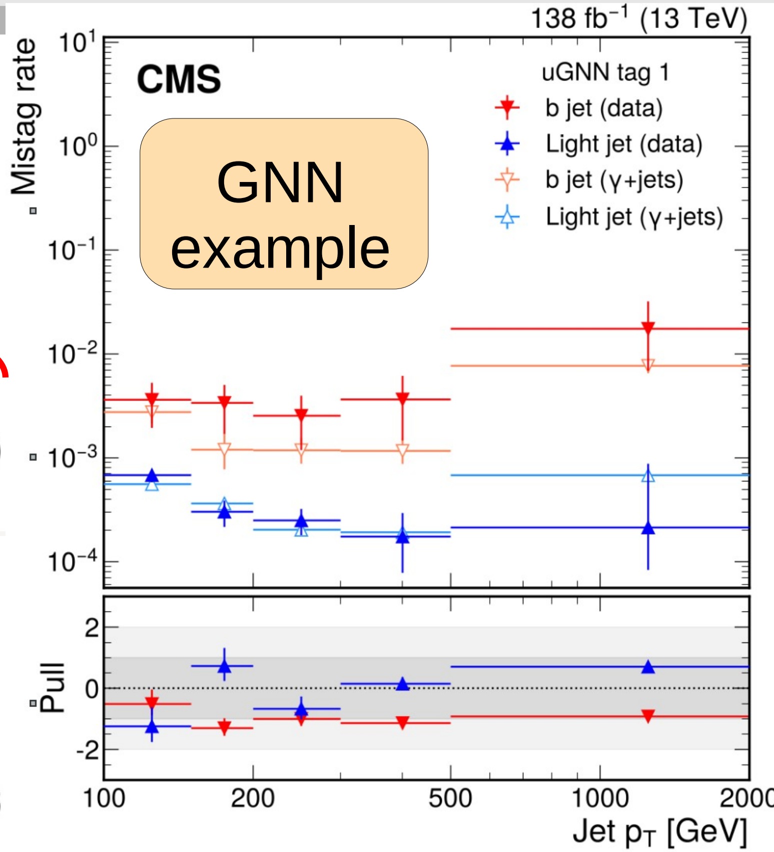

- $c\tau_{\pi_{dark}}$ $1 - 1000$ mm
- EJ contained within tracker
- Cut-based
  - Unflavored: leverage track displacement
  - Flavor-aligned: leverage track multiplicity
- Graph neural network
  - 2 models trained separately on unflavored and flavor-aligned scenarios

# Emerging Jets: Bkg. Estimation

EXO-22-015

- Data-driven bkg estimate, based on mistag rate of EMJs
- Split by **light** vs **b flavor**

$$N_{SR} \sim \sum_{evt \in CR} \frac{1}{2} \sum_{j \notin tagged} B^{CR} \epsilon(b, p_{T,j}) + (1 - B^{CR}) \epsilon(l, p_{T,j})$$




| | | | |
|---|---|---|---|
| GNN unflavored | uGNN set 1 | $15.6\ ^{+5.4}_{-1.9} \pm 3.8$ | 18 |
| | uGNN set 2 | $0.73\ ^{+0.44}_{-0.16} \pm 0.27$ | 0 |
| | uGNN set 3 | $7.6\ ^{+3.5}_{-1.3} \pm 2.3$ | 9 |
| GNN flavored | aGNN set 1 | $45\ ^{+18}_{-8} \pm 16$ | 59 |
| | aGNN set 2 | $0.30\ ^{+0.23}_{-0.07} \pm 0.18$ | 1 |
| | aGNN set 3 | $3.8\ ^{+2.2}_{-0.7} \pm 2.0$ | 5 |

No statistically Significant Excess over bkg

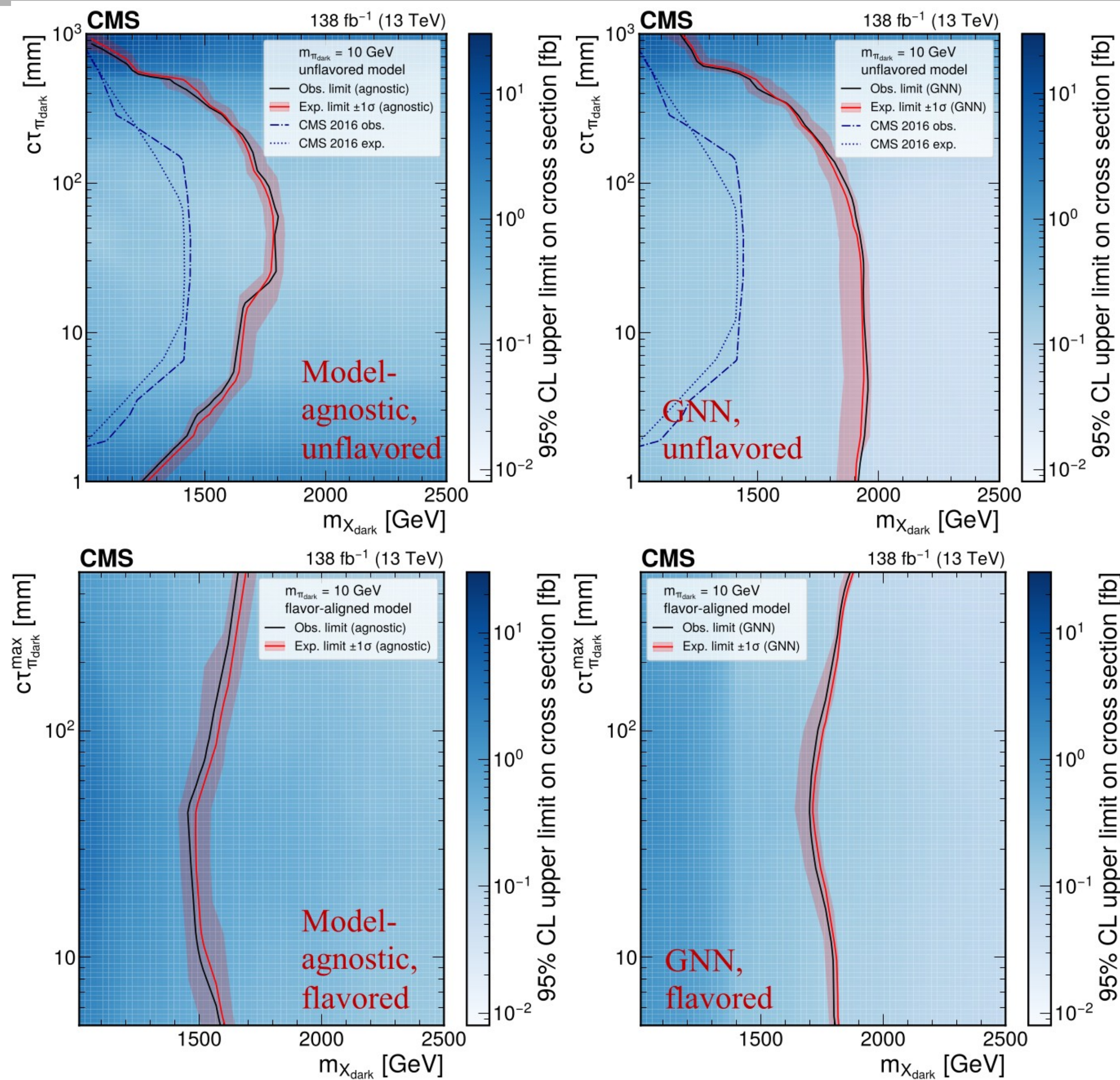
- (And analogously for cut-based, model-agnostic selection)

# Emerging Jets: Results

EXO-22-015

- Improved limits on 10 GeV dark pion
- New limits for unflavored 20 GeV dark pion
- New for all flavor-aligned models

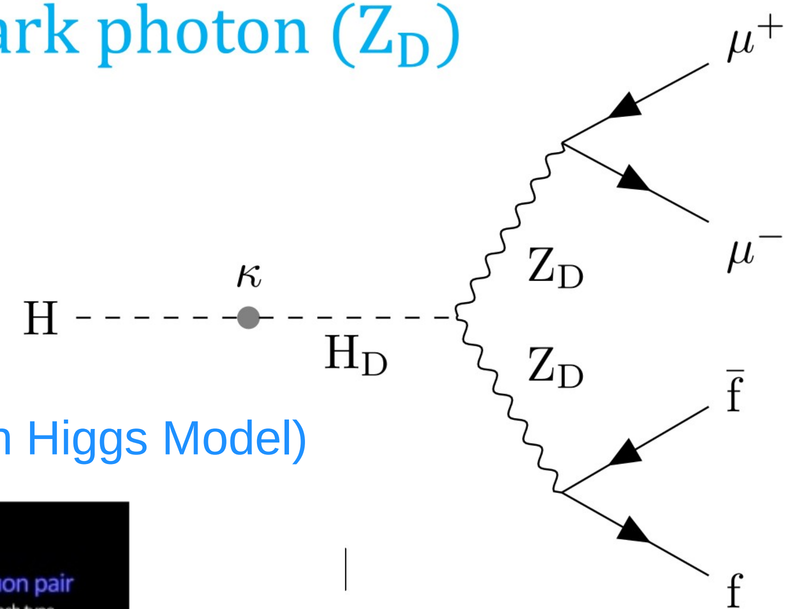
Use of GNN: better limits by 150-600 GeV everywhere



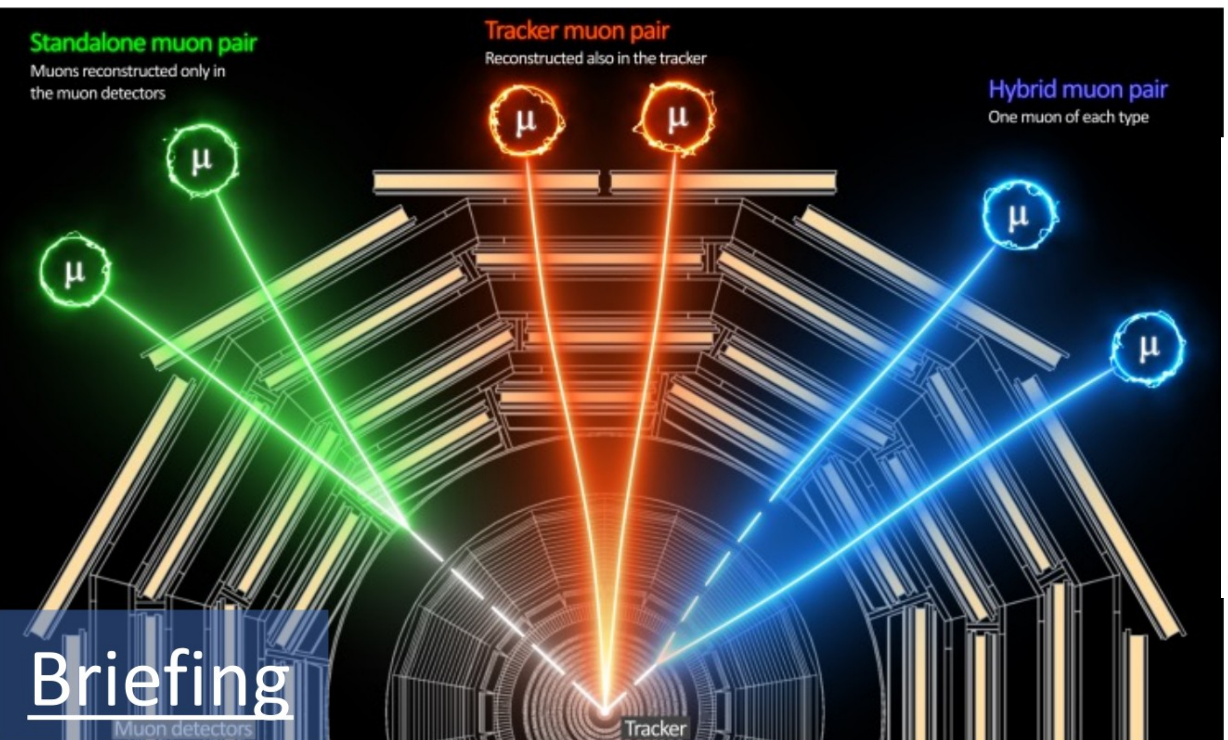
# Displaced dimuons: Model + signature

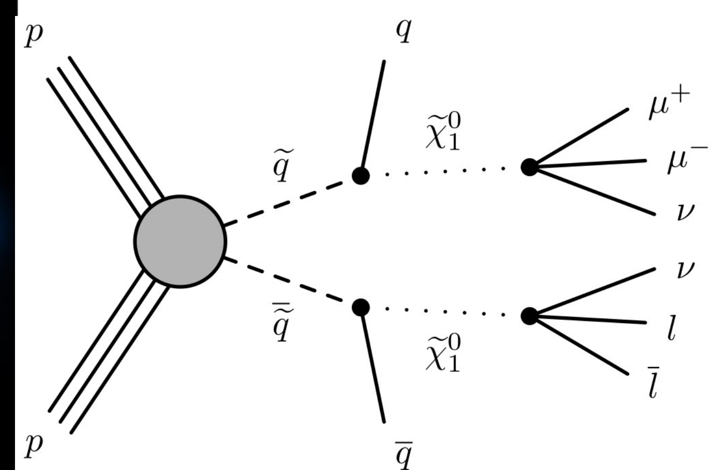
- ≥1 dimuon pair
  - (muon pT> 10 GeV),
- selected in 2022 data (36.6 fb-1)
- Run3: new triggers for displaced dimuons!

Dark photon ($Z_D$)




(Hidden Abelian Higgs Model)



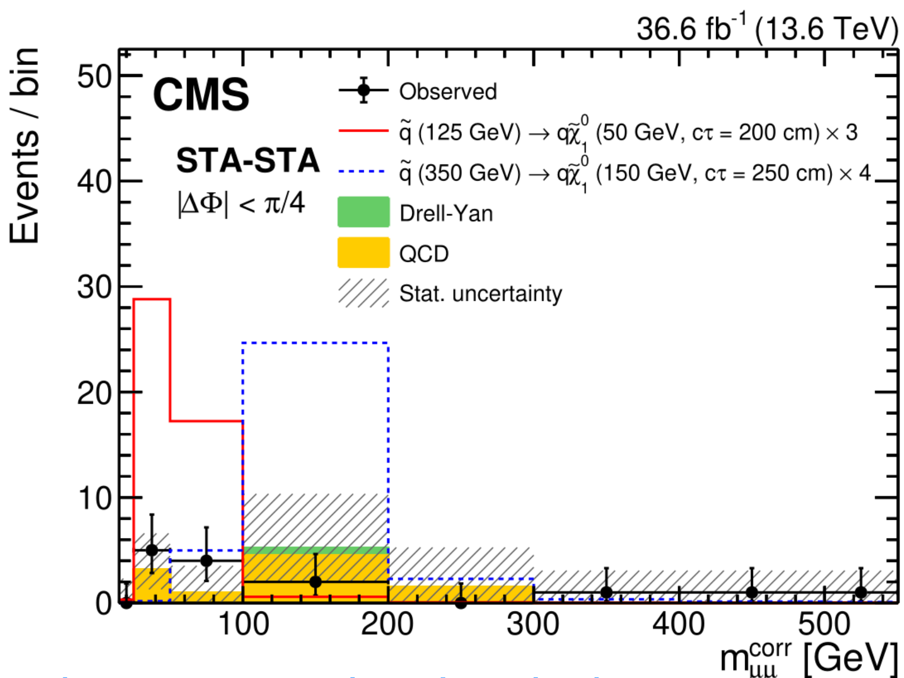

(RPV SUSY)

EXO-23-014

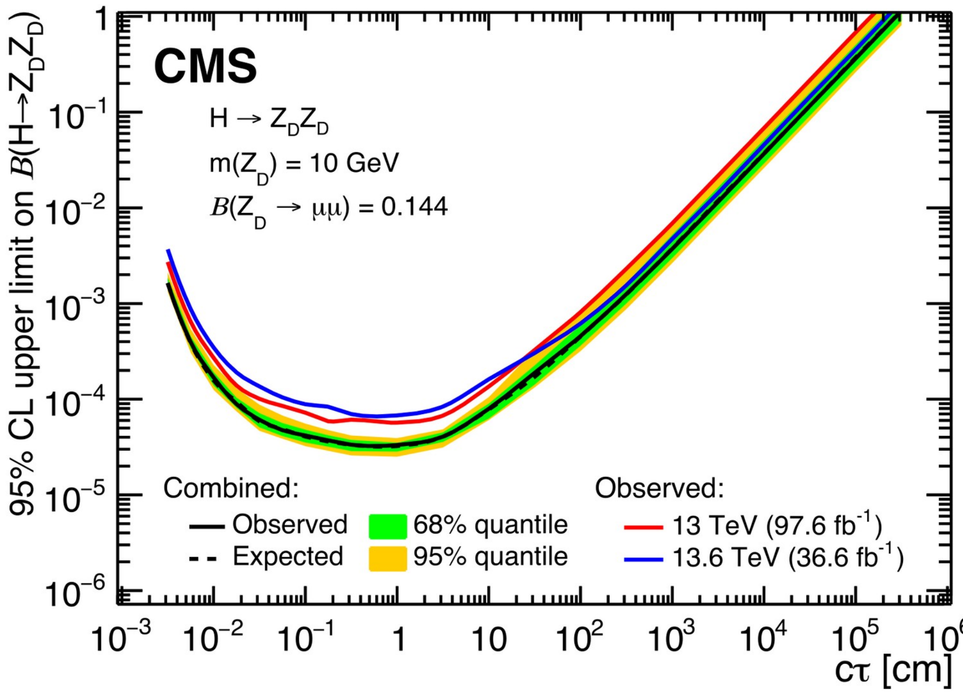
# Displaced dimuons: results

EXO-23-014

- Background estimated separately in all three categories
- Limits on HAHM and on wino and higgsino DM




(RPV SUSY signal region)




- Achieved sensitivity of Run 2 with only 1/3 of Run3 lumi !
- Improved constraints on $\mathcal{B}(H \to Z_D Z_D)$ by ~ 2x

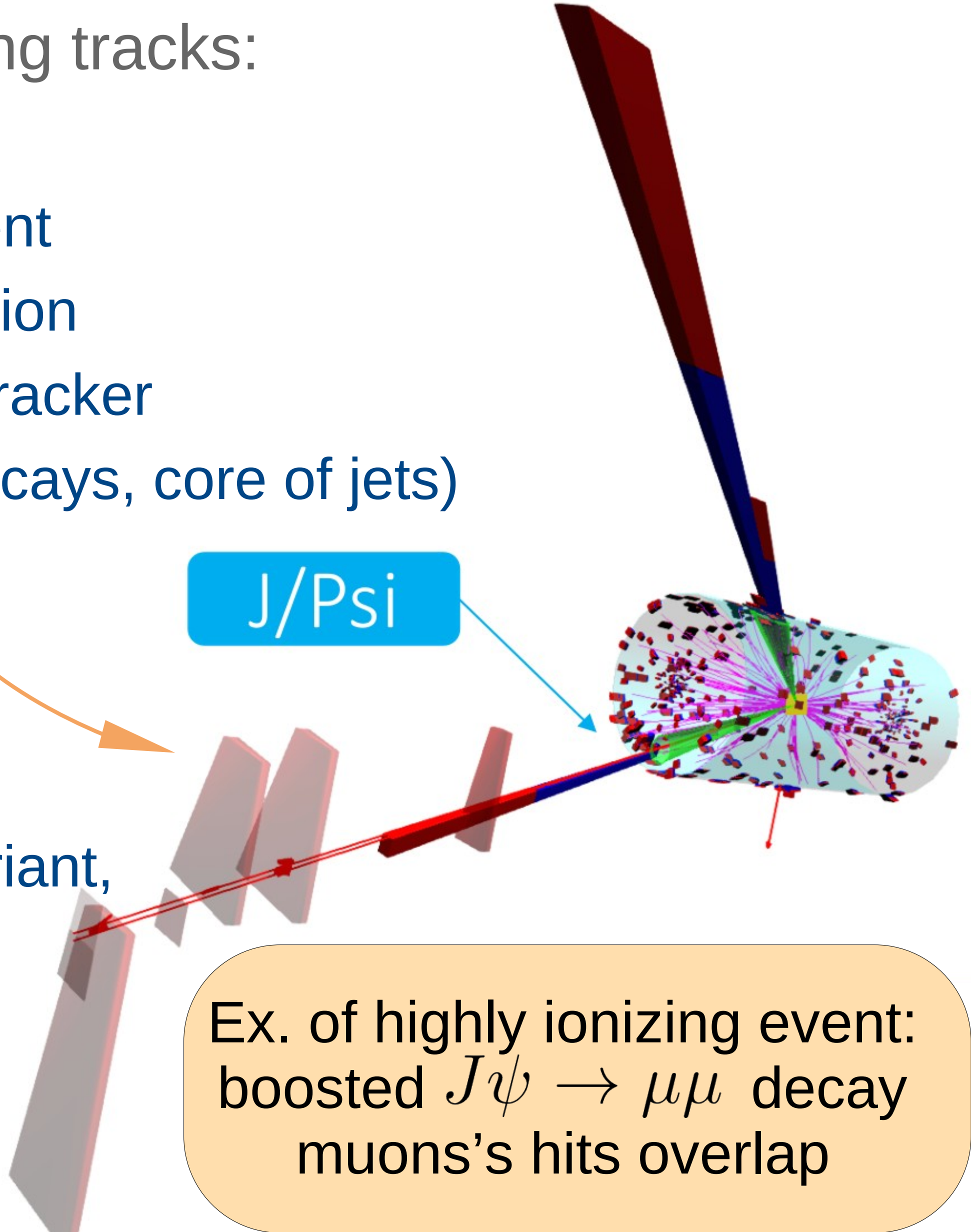
# Conclusions

- LLP program at LHC is a very active and dynamic field of research
- New ideas, diversity of approaches:
  - use of new triggers,
  - improved tracking and vertexing algorithms,
  - machine learning taggers,
  - different analysis strategies/techniques, …
- Run 3 data analyses in full swing

# BACKUP MATERIAL

# HSCP: Selection, backgrounds

- SM sources of highly ionizing tracks:
  - Fake tracks
  - Bad ionization measurement
  - Tail of the Landau distribution
  - Overlapping tracks in the tracker (pileup, boosted meson decays, core of jets)
- Preselection:
  - $p_T > 55$ GeV
  - Track isolation
  - `Mini' isolation (boost invariant, includes calorimeter info)
  - general track/hit clean-up
  - no 2016 data




Ex. of highly ionizing event: boosted $J\psi \to \mu\mu$ decay muons's hits overlap

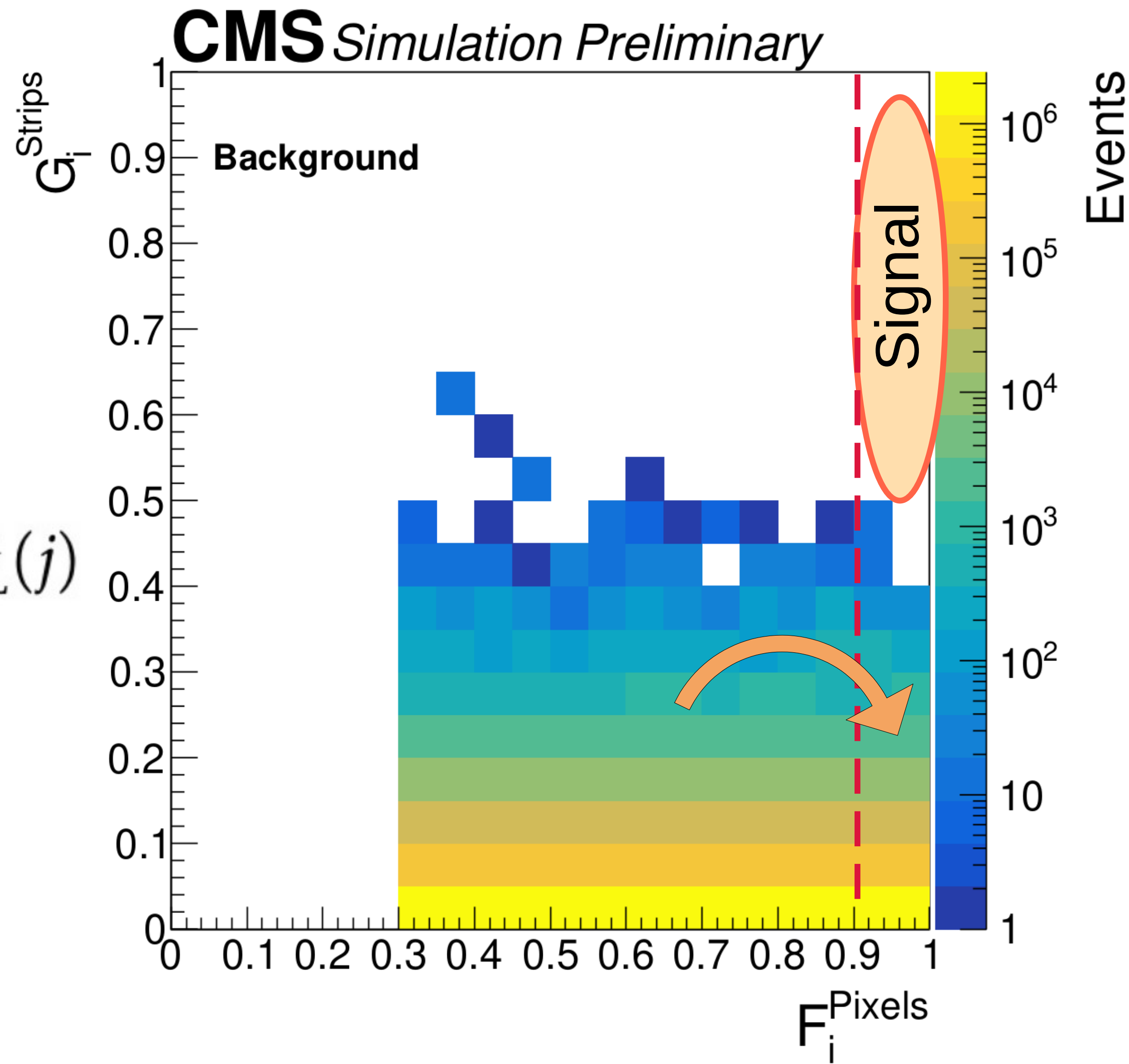
# HSCP: 'Ionization method'

EXO-18-002

- F and G and uncorrelated, and F is flat for bkg...

- Use sideband of F to predict shape of G in signal region

$$N_{\rm PASS}^{\rm bkg}(j) = R_{\rm P/F}(j)\, N_{\rm FAIL}^{\rm data}(j)$$

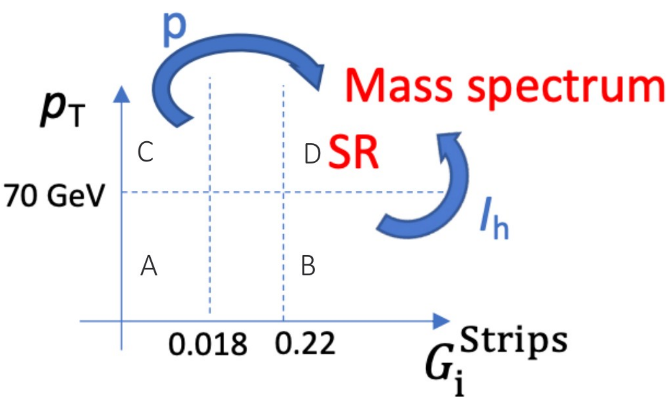


# Bkg estimation #2: `Mass method'

EXO-18-002

- Data-driven: assume independence of $I_h$ and $p$, and of $p_T$ and $G_i^{\mathrm{Strips}}$. Note lower $p_T > 70\ GeV$

  - ABCD method to determine every bin in mass spectrum




  - Fit $I_h$ shape in B and $p$ in C, in bins of $\eta$, use to predict m in SR.